MULTIVALUE MAGNETORESISTIVE READ/WRITE MEMORY AND
METHOD OF WRITING TO AND READING FROM SUCH A MEMORY

5 The present invention relates firstly to a magnetoresistive read/write memory according to the preamble of patent claim 1. Furthermore, the invention relates to a method of writing to such a memory according to the preamble of patent claim 7 and to a method of reading from such a memory according to the

10 preamble of patent claim 11.

Magnetoresistive read/write memories, which are referred to as MRAM memories (magnetoresistive random access memory), are memories in which data can be

15 stored and also read again at one address. The memories generally have one or more storage cells, the storage effect residing in the magnetically variable electrical resistance of the storage cell or the storage cells.

20 Hitherto the development concerned using single-value storage cells, as they are known, with a binary storage content for the magnetoresistive memories. These storage cells comprise two intersecting electric conductors, which are preferably aligned at right

25 angles to each other. At the intersection between these conductors, there is a layer system comprising two magnetic layers, one of the layers being formed from soft magnetic material and the other layer from hard magnetic material. Between the magnetic layers there is a tunnel oxide. Such a storage cell is described in the

30 figure description in connection with fig. 1. Depending on the state of magnetization, the magnetization directions in the magnetic layers can be aligned in parallel or antiparallel. Depending on the magnetization direction in the magnetic layers, the storage cell has a different electric resistance. In this case, a parallel magnetization direction leads to a lower electrical resistance of the storage cell.

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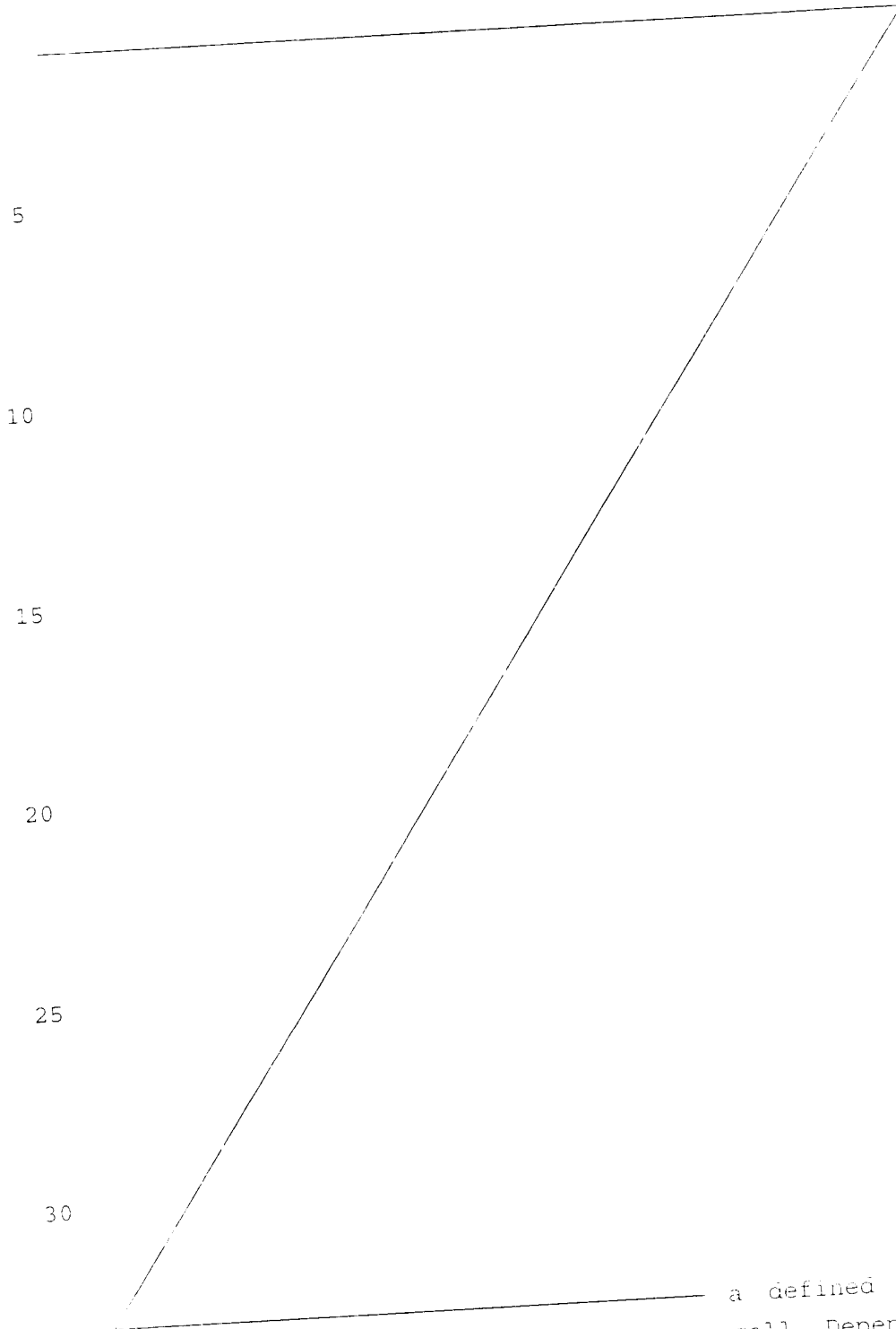
a defined item
of information is written to the memory cell. Depending
on whether the storage cell experiences a change in its
information content in the process, a current or
voltage pulse, or else the absence of such a pulse, can

be detected on the corresponding read line. In this case, each read operation results in a loss of information from the cell. In order to compensate for this loss, the information read out is written back to the storage cell again after the read operation has been completed.

US-A-5,734,505 discloses a single-value MRAM storage cell in which two or more magnetic layers are arranged between two electric conductors. Because of ferromagnetic coupling between the magnetic layers, their magnetization directions are always oriented in parallel with each other in the absence of a magnetic field. The information stored in the storage cell is encoded in the direction of the common orientation of the magnetic layers. In order to read the information, a possible change in the electrical resistance of the layers, based on the large magnetoresistive effect, is detected by a magnetic field which is sufficient to fold over the magnetization direction of a first magnetic layer but is not sufficient to fold over the magnetization direction of a second magnetic layer being applied.

With regard to the problem of the increased area requirement of single-value storage cells in order to achieve powerful memory systems, in recent times multivalue storage concepts have been developed, but have hitherto been proposed only for other types of memories than MRAMs. Such a memory type is, for example, an EEPROM (electrically erasable PROM), which may be written to and erased electrically. In this case, specific subregions of a basically continuous value range are set equal to discrete states. Assignments of this type cannot be performed in the MRAM storage cells, since no storage of continuously variable information is possible. This is because, on the basis of their principle, MRAM storage cells

fundamentally constitute a system with a finite number of discrete states. The approaches to multivalency with regard to the aforementioned EEPROM's cannot therefore be transferred to the magnetoresistive memories.

Jeong et al. (Jeong, WC, Lee, BI, Joo, SK (1998) "A New Multilayered Structure for Multilevel Magnetoresistive Random Access Memory (MRAM) cell", IEEE Transactions on Magnetics, US, IEEE Inc., New York, Vol. 34, No. 4, Part 01, pp. 1069-1071) have shown, by using a layer sequence of magnetic nickel-iron, nickel-iron/cobalt and cobalt layers, in each case separated from one another by a copper intermediate layer and formed on a silicon copper double layer, that because of different coercivity field strengths of the three magnetic layers, the magnetization directions of the magnetic layers can be folded over individually by means of applying a tuneable magnetic field. This phenomenon was measured by using a respectively abrupt change in the resistance of the layer sequence, detected by means of a four-point measurement, resulting from the large magnetoresistive effect. Furthermore, Jeong et al. propose to set the individual magnetization directions of the magnetic layers in a sequence beginning with the magnetic layer with the highest magnetic hardness down as far as that magnetic layer with the lowest electric hardness

Also known with regard to multivalue structures is US-A-5,585,986, which discloses a digital magneto-resistive sensor for reading from a magnetic data storage system. This sensor has a multilayer structure, whose electrical resistance is measured. The multilayer structure comprises a number of ferromagnetic layers, the magnetic moments and therefore the magnetization directions of the individual layers being influenced by an external magnetic field, which is generated by the corresponding data carrier.

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magnet field strengths. In this way, the resistance
of the sensor changes in graduated steps when the
external magnetic field is varied, which produces a
digital output signal.

On the basis of the aforementioned prior art, the
intention is to provide a magnetoresistive read/write
memory and a method of writing to and reading from such
a memory in which the disadvantages and problems
described in relation to the prior art are avoided. In
particular with regard to a possible saving of area,
an improved MRAM memory and a suitable method of
writing to and reading from such an MRAM memory are to
be provided.

According to the first aspect of the invention, this
object is achieved by a magnetoresistive read/write
memory having one or more storage cells, each storage
cell having two intersecting electric conductors and a
layer system comprising magnetic layers located at the
intersection of the electric conductors. According to
the invention, the memory is characterized in that the
layer system is designed as a multilayer system with
two or more magnetic layers, in that at least two, but
a maximum of all the magnetic layers have a
magnetization direction that can be set independently
of one another, and in that the magnetization direction
in the individual layers is changed or can be changed
on the basis of the electric current flowing through
the electric conductors.

In this way, a multivalue memory having one or more
multivalue storage cells and therefore with a
correspondingly high storage capacity is created.
Furthermore, this memory or the at least one storage
cell can be written to and/or read from in a simple
way.

A fu... ...l feature of the memory according to the inven... ... of the storage cell or storage cells formin... ... memory consists in using an n-layer mul... ...ystem with n greater or equal to two magn... ...rs at the intersection of the two electric condu... ... it being possible for the magnetization direction ... m layers, with n greater than or equal to m and ... ...eater than or equal to two, to be set indepen... ...ly of the magnetization direction in the other ... . While in the case of the single-value memori... ... magnetization direction is set in only one magne... ...er, in the case of the multivalue memories accor... ... the invention, this can now be carried out in an ... ...d number of magnetic layers. In this case, the n... ... magnetic layers can vary depending on the requirem... and application, so that the invention is not ... ...ed to a specific number of layers. A simil... ...layer system has in principle already been desc... ... US-A-5,585,985.

A fur... ...ndamental feature for the memory according to the ... ...ion is that the magnetization direction in the indiv... ...ual layers is changed or can be changed on the basi... ...f the electric current flowing through the elect... ...ductors.

In ord... ... be able to set the magnetization directions in the ... ...idual magnetic layers independently of one ano... ... ...s necessary to achieve the situation where the ... ...ng of the magnetization direction (remag... ...tion) in the individual layers is brought about ... ...spectively different field strengths or curr... ...e conductors.

In US ... ...,985, this requirement is achieved by the multi... ...ystem having a crystalline structure and by the ... ...nal layers having different crystalline symme... ... and therefore magnetic anisotropies. Furth... ... the layers have a different thickness and

layer ... ogy. If the multilayer system is exposed
to a ... field with a respectively specific field
stren... ... magnetization direction in individual or
sever... ... is either changed or not on the basis of

5   the ... rength of the magnetic field applied and
the ... configuration of the respective layer.
Be... ... complex manufacturing operation for the
multi... ... system, such a system is particularly
compli... ... and costly.

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With ... ... agnetoresistive memory according to the
inven... ... different route is followed. This route
permi... ... manufacture of magnetic layers with
subst... ... identical structures and morphologies.

15   The ... ive, individual setting of the magnetization
direct... ... the individual layers is brought about
via ... ... ely different field strengths by means of
diff... ... rrent intensities. For this purpose, in
each ... ... electric current flows through the two

20   inter... ... conductors, on the basis of which current
a ma... ... eld is in each case formed around the two
cond... ... The magnetic field acts on the individual
magne... ... rs of the multilayer system, as a result
of wh... ... latter can be remagnetized in the event of

25   adeq... ... igh field strengths. The remagnetization of
indiv... ... yers therefore depends on the magnitude of
the ... ... flowing through the two conductors and the
physi... ... ngement of the respective magnetic layer
in re... ... the electric conductors.

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The ... ... ting conductors into which the current
prod... ... field is impressed therefore function as
a sui... ... ad and/or write tool for the memory. While
in th... ... f single-value memories, a fixed current

35   is im... ... into the conductors and either changes the
magn... ... direction in the remagnetizable magnetic
laye... ... in connection with the present invention
use ... ... f the fact that a change in the magnetic
fie... ... is suitable to set the magnetization

di_____ a large number of magnetic layers indep_____ of one another and individually. The pr_____ different magnetic field strengths can be carried ___ in various ways, as will be explained in

5 more detail in the further course of the description.

Advantageous embodiments of the memory according to the invention emerge from the subclaims.

10 The magnetization directions that can be set independently of one another in the individual layers can preferably be set or can be capable of being set via different current intensities. This can be carried out in different ways, depending on the configuration

15 of the storage cells. For example, it is conceivable for _____ with different current intensities to be impress___ ___ the electric conductors in order to set different magnetization directions in individual magnetic layers. As a result of the different current

20 intensities in each case different field strengths are produced, which then lead to a change in the magnetization direction in one or more layers or not.

In a further refinement, the electric conductors can be

25 designed for high current densities.

The individual magnetic layers are preferably formed from a ferromagnetic material. However, the invention is not restricted to specific material types, so that

30 other suitable materials are also possible.

The _____ng electric conductors can advantageously be a_____ orthogonally to one another.

35 In a further refinement, in each case a tunnel dielectric is provided between two adjacent magnetic layers. The electronic conductivity through such a multilayer system comprising magnetic layers and tunnel dielectric layers lying between them is substantially

determines the tunnel effect through the tunnel dielectric. The selection of a suitable thickness for the tunnel dielectric is therefore of particular importance, since variations in the layer thickness

5 lead to considerable variations in the conductivity, since the thickness of the layer enters approximately exponentially into the tunnel current. Preferably - but not exclusively - thin tunnel dielectric layers with a thickness of 2 to 3 nanometers (nm) are therefore

10 used.

According to a second aspect of the present invention, a method of writing to a magnetoresistive read/write memory according to the invention as described above is

15 provided which, according to the invention, is characterized by the following steps: a) impressing a variable electric current into the two electric conductors and, as a result, producing a magnetic field and b) setting the magnetization direction in

20 the individual magnetic layers of the multilayer system via the field strength of the magnetic field produced, the magnetization directions in the individual layer being set independently of one another via respectively differently high requisite field strengths, in such a

25 way that the magnetization directions are set first in those layers which need the highest field strength for the purpose, and that the magnetization directions are then set in those layers which respectively need a lower field strength for the purpose.

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As a result of the method according to the invention, it becomes possible in a simple way to write to a multilayer magnetoresistive memory or its storage cell or its cells. According to the invention, the

35 sequence in which the information is stored in the individual magnetic layers must be selected in such a way that the layers of a memory cell are written to in the sequence of decreasing field strength for the remagnetization of the layers (which means with

programming current intensities respectively adapted in accordance with the field strength desired on the corresponding layers. This ensures that information that has already been written to the storage cell and

5 has been written into a layer with a higher programming field strength is not overwritten again when information is written to further layers, which are then written to with respectively lower programming field strengths.

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In relation to the advantages, reactions, effects and the functioning of the method according to the invention, reference is hereby also made further to the full disclosure of the above explanations relating to

15 the memory according to the invention. Advantageous refinements of the method according to the invention emerge from the subclaims.

The different field strengths acting on the layers can

20 preferably be produced by currents of different magnitudes being impressed into the conductors. The different field strengths acting on the layers are further determined by a different physical spacing of the layers in relation to the electric conductors.

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Furthermore, it is also conceivable that for setting the magnetization directions in the layers on the basis of field strengths of different magnitudes, is influenced by characteristics of the layer material

30 and/or the layer thickness and/or the layer morphology.

Since the aforementioned examples have already been described extensively further above, reference is made at this point to the embodiments cited.

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According to the third aspect of the present invention, a method of reading from a magnetoresistive read/write memory according to the invention as described above is provided which, according to the invention, is

characterized by the following steps: a) impressing a
defined item of data into the individual layers of the
multilayer system in such a way that the item of data
is first impressed into that layer which needs the

5 lower field strength to set the magnetization
direction, and that the item of data is then impressed
into the layers with the respectively next higher
requisite field strength; and b) detecting a possible
information change in the layer or the layers on the

10 basis of the defined item of data impressed.

By means of the method according to the invention, a
multilayer magnetoresistive memory can be read out in a
simple way. In relation to the advantages, actions,
effects and the functioning of the method according to

15 the invention, in addition to the following
description, reference is hereby made to the full
disclosure of the above explanations relating to the
memory according to the invention and to the method

20 according to the invention for writing to a memory.

The basic idea of the method according to the invention
for reading from a memory is that in each case a
specific item of data, that is to say a specific item
of information, is written successively to the

25 individual magnetic layers of the storage cell or of
the storage cells. If the information content of the
layer changes following the impression of the specific
item of data, this means that the layer had previously
been written with a different item of information. If

30 the information content of the layer does not change
following the impression of the specific item of data,
this means that the layer had previously also been
written with the same item of information. In this

35 case, it is of particular importance that the item of
target data is known. The item of target data is to be
understood to mean that item of data which, as
described above, is specifically written to the storage
cell.

The possible information change or the absence of an information change can be detected in a suitable way and then evaluated. Exemplary embodiments of this will be explained in more detail in the further course of the description.

In order to be able to carry out the action of reading from the storage cell or storage cells of the memory in an optimum way, first of all those layers are read, that is to say specifically rewritten with the specific item of data, which need the lowest programming field strength in order to set the magnetization direction. The specific item of data is therefore written to the storage cell or the individual layers of the multilayer system of the storage cell in the sequence of increasing programming field strength.

Advantageous embodiments of the method according to the invention emerge from the subclaims.

The possible information change in the layer or the layers can preferably be discovered by measuring the electrical resistance. Since the electrical resistance of the storage cell depends on the magnetization directions (parallel or antiparallel) of the individual layers, and the magnetization directions can change on the basis of possible information changes, a change in the electric resistance means that the information content of the storage cell or of individual layers of the memory cell has changed.

In addition, the possible information change in the layer or the layers can be carried out via detection of current and/or voltage pulses. If the action of writing the specific item of data to the layers of the storage line leads to an information change, a current and/or voltage pulse also occurs in the process, and can be detected. For the case in which no current and/or voltage pulse is detected, this means that no

information change has taken place either in the layer
or the layers.

The detection of a possible information change in the
5   layer or the layers can preferably be carried out
before and after the impression and/or during the
impression of the specific item of data into the layer
or the layers.

10   In an advantageous refinement, a specific item of data
with respectively the same value can be impressed
successively into all the layers. If information in
binary form, that is to say with logic values "1" and
"0", is stored in the storage cells, the specific item
15   of data which is written successively to all the layers
of the storage cell can have either the logic value "1"
or "0".

In another refinement, it is also conceivable for an
20   item of data which belongs to an alternating algorithm
to be impressed successively into the layers.

The results during the detection of a possible
information change for each layer can advantageously be
25   stored intermediately, at least temporarily, in a
suitable storage device.

The invention will now be explained in more detail
using exemplary embodiments and with reference to the
30   appended drawing, in which:

Fig. 1a shows a schematic perspective view of a
magnetoresistive storage cell according to the
prior art;

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Fig. 1b shows a schematic cross-sectional view of the
storage cell according to Fig. 1a;

Fig. 1c shows an equivalent circuit for a storage cell according to Fig. 1a;

Fig. 2 shows a schematic cross-sectional view of a first embodiment of a multivalue memory cell according to the invention, a two-value memory cell here, different magnetization states being illustrated in the partial views a) to d); and

Fig. 3 shows a cross-sectional view of another embodiment of the multivalue storage cell according to the invention.

Figs. 1a to 1c show a storage cell 11 of a magnetoresistive memory 10 according to the prior art. The storage cell 11 is designed as a single-value storage cell and has an upper 12 and a lower 13 electric conductor, which are aligned orthogonally to each other and intersect at an intersection of the storage cell 11. At the intersection there is a layer system 14 with two magnetic layers, a hard magnetic layer 15 and a soft magnetic layer 16. Between the layers 15, 16 there is a tunnel dielectric 20. For the storage cell 11, an equivalent circuit according to Fig. 1c can be specified, the value of the resistance 19 contained therein between the conductors 12, 13 depending on whether the magnetization directions 17, 18 in the magnetic layers 15, 16 are in parallel or antiparallel. The example according to Fig. 1b shows an antiparallel alignment of the magnetization directions. A parallel magnetization direction leads to a lower resistance value, while an antiparallel magnetization direction leads to a higher resistance value

In order to write to the storage cell 11, high electric currents are impressed simultaneously into the conductors 12, 13. The magnetic field generated by these currents at the intersection of the conductor

12, it has an adequately high field strength there for the magnetization of the soft magnetic layer 16.

The storage cell 11 and the memory 10 formed from one
5   or more such storage cells 11 need a relatively large area.

In order to circumvent this disadvantage, a multivalue memory having multivalue storage cells is proposed. Two
10 exemplary embodiments of such storage cells according to the invention are described in figs. 2 and 3.

Fig. 2 shows in schematic form a two-layer 2-bit storage cell 11, as it is known. Between the two
15 electric conductors 12, 13, at their intersection, there is a multilayer system 30 with a plurality of magnetic layers 31, 32 and tunnel dielectrics 35 in each case arranged between them.

20 In principle, the multilayer system has n magnetic layers the condition $n \geq 2$ applying. Of these n layers, the magnetization direction can be set in m layers independently of the other adjacent layers, it being true that: $n \geq m \geq 2$.

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In the exemplary embodiment according to fig. 2, two magnetic layers 31, 32 are illustrated, whose magnetization directions 33, 34 can in each case be set independently of one another. The part views 2a to 2d
30 of fig. 2 in this case show the different possible magnetization states or magnetization directions 33, 34 in the magnetic layers 31, 32.

For the following explanation of the information
35 content of the storage cell 11, the nomenclature introduced will be to name the magnetization directions with corresponding reference numbers, such as logic "0" and logic "1", the magnetization directions being described with increasing magnitude of the reference

numbers for the magnetic layers counted from top to
bottom. Logic "0" stands for the magnetization
direction "from left to right" shown in figs. 2 and 3,
logic "1" stands for the magnetization direction "from
5   right to left" shown in figs. 2 and 3.

According to fig. 2 and the part views shown therein, a
total of four different magnetization states can be set
in the magnetic layers 31, 31. According to fig. 2a, in
accordance with the nomenclature introduced above, a
10 logic "0" applies to the set magnetization direction
33, while a logic "0" likewise applies to the
magnetization direction 34. According to Fig. 2b, the
result is 33 = "0" and 34 = "1". fig. 2 shows the
magnetization state 33 = "1" and 34 = "0", while
15 fig. 2d shows the magnetization state 33 = "1" and
34 = "1".

A further exemplary embodiment of a storage cell 11 is
shown in fig. 3. The storage cell 11 again has two
20 intersecting electric conductors 12, 13 and a
multilayer system 40 which is located at the
intersection of the conductors 12, 13 and in the
present case is formed of five magnetic layers 40-45,
in which the respective magnetization directions 46-50
25 can in each case be set independently of adjacent
layers. There is in each case a tunnel dielectric 51
between the magnetic layers.

According to the nomenclature introduced above, the
30 storage cell 11 according to fig. 3 has the following
magnetization state: layer 41 has a magnetization
direction 46 with logic "0", layer 42 has a
magnetization direction 47 with logic "1", layer 43 has
35 a magnetization direction 48 with logic "1", layer 44
has a magnetization direction 49 with logic "0" and
layer 45 has a magnetization direction 50 with logic
"1".

In order to be able to write specifically to the storage cells 11 explained above, the various magnetic layers 31, 32 or 41-45 must satisfy the requirement that different current intensities in the

5 field-producing conductors 12, 13 are needed for their remagnetization. This can be achieved by respectively different magnetic field strengths being required in the individual layers. In this case, currents of different magnitudes can be impressed into the

10 conductors 12, 13 and then produce the different field strengths for the remagnetization of the individual layers. At the same time, in order to provide field strengths of different magnitudes to set the magnetization directions in the individual layers, use

15 is also made of the different physical spacing between the layer respectively to be remagnetized and the conductors 12, 13.

The sequence of storing the information in the

20 individual layers 31, 32 or 41-45 of the storage cell 11 must be selected such that the layers of the storage cell are written to in the sequence of decreasing programming field strength. This means that first of all those layers which need the highest field strength

25 to set the magnetization direction are written to first, while those layers which respectively need a lower field strength for this purpose are subsequently written to. This ensures that information that has already been written into the storage cell 11 and

30 initially was written into a layer with a higher programming field strength cannot be overwritten again when information is being written into further layers.

For the reading procedure, according to the invention a

35 method is specified which, for example, is based on the direct measurement of the resistance or on the detection of current and/or voltage pulses when a defined item of information is impressed into the corresponding bit of the storage cell 11 to be read.

The information content of the storage cells 11 is in principle changed during the complete read operation. However, no additional reference storage cell is needed.

The reading method will now be described by way of example using an m-bit cell, which is designed as a 2-bit cell. This cell has exactly m (with m = 2) remagnetizable layers, each of which has a magnetization direction MR_k, ME_k describing the magnetization direction of the kth magnetic layer, counting from top to bottom, where $1 \leq k \leq m$. The storage cell contains the data D_k present in binary form, where $1 \leq k \leq m$. In order to read from this cell, a defined item of data $E_k = E_{fix}$, where $1 \leq k \leq m$, is written to this cell in the sequence of increasing programming field strength (first of all, therefore, into those layers which need a low field strength in order to set the magnetization direction). For example, for all k, this item of data can have the logic value "0" or "1".

Before the start of this read operation, it is therefore true that $MR_k = D_k$, and after it has been concluded, $MR_k = E_{fix}$, for all layers k with $1 \leq k \leq m$.

For the case in which a current and/or voltage pulse is detected during the kth write operation, this is a positive indicator that a change has taken place in the corresponding kth item of data, that is to say it is true that $D_k =$ the item of data that is the complement of E_{fix}. Before the defined item of data E_{fix} was read into the layer, the latter therefore had stored the item of data that was the complement of E_{fix}. For the case in which no current and/or voltage pulse is detected, it is true that $D_k = E_{fix}$. Thus, after the read operation has been completed, the complete binary data from the storage cell is available.

As an alternative to the detection of a current and/or voltage pulse, a measurement of the electrical resistance in each case before and after the impression of the defined item of data Efix into the corresponding

5 bit can also be performed for each write operation. In the case of an m-bit cell, a 2-bit cell in the present case, this means that a total of m+1 measurements, three measurements in the present case, have to be performed. The individual measured values for each

10 layer are intermediately stored, at least temporarily, in a suitable storage device. For the case in which, during the measurements relating to the kth bit, the resistance values before and after the impression of the item of data Efix are different, it is true that Dk

15 before the impression of the item of data Efix was originally the item of data that is the complement of Efix. In the case of identical resistance values before and after the impression of the item of data Efix, the result is Dk = Efix.

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The reading method cited above was used to read out 2-bit cells. However, similar methods are also possible for m-bit cells with m > 2.